Pion Form Factor Measurements

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- Motivation
- F_π measurements
- Summary

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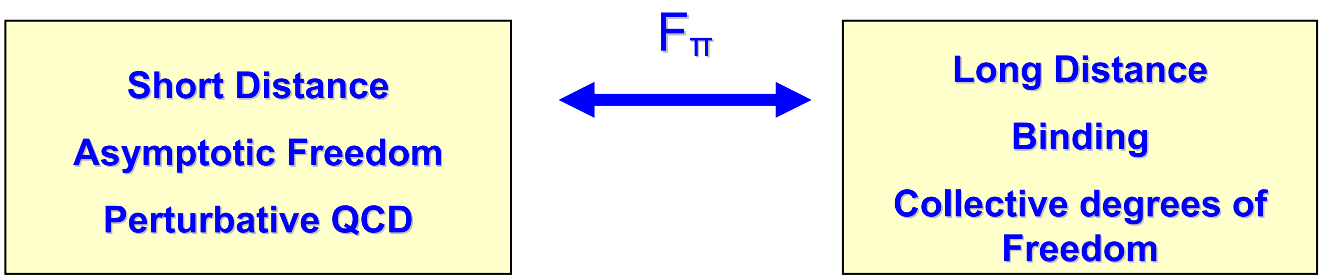
Hadronic Form Factors in QCD

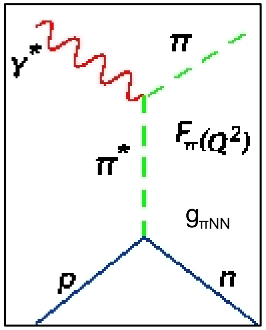
- Fundamental issue: quantitative description of hadrons in terms of underlying constituents
  - Theory: Quantum Chromo-Dynamics (QCD) describes strong interactions
  - Degrees of freedom: quarks and gluons

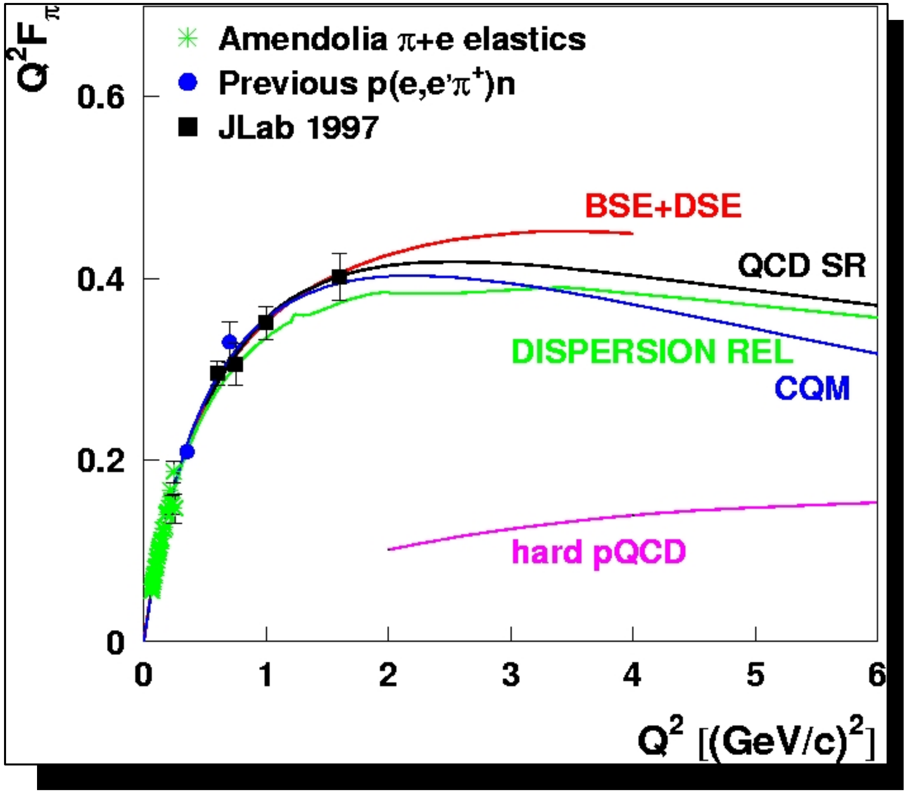


- Studies of the transition between short/long distance scales:
  - Theory – Lattice, GPD's, QCD inspired models
  - Experiments – form factors, color transparency, quark counting rules, nuclear filtering, duality

Pion Electric Form Factor $F_\pi(Q^2)$ and pQCD

- F_π can be calculated in pQCD at very high Q^2, scales ~$1/Q^2$
- F_π can be measured directly from π+e scattering (*S.R. Amendolia et al., NP* ***B277*** *(1986)*) up to Q^2~0.3 GeV^2
- No "free pion" target – to extend measurement of F_π to larger Q^2 values use "virtual pion cloud" of the proton



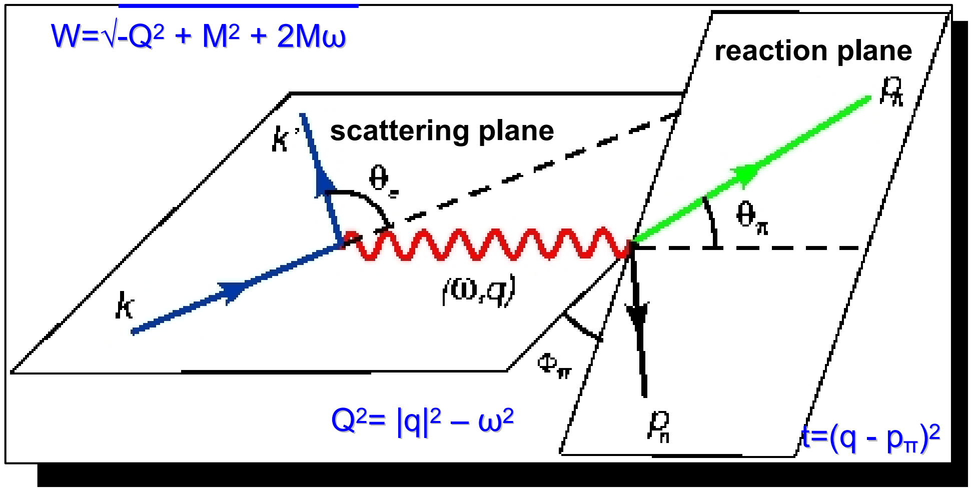


V.A. Nesterenko and A.V. Radyushkin, Phys. Lett. **B115** (1982) 410

P. Maris and P. Tandy Phys Rev **C61** (2000)

C.-W. Hwang, Phys Rev **D64** (2001)

Extracting F_π from Pion Electroproduction Data



- The lab cross section can be expressed:

$$\frac{d\sigma}{dE\,d\Omega_e\,d\Omega_\pi} = \Gamma_v\,\mathcal{J}(t,\varphi \to \Omega_\pi)\,\frac{d^2\sigma}{dt\,d\varphi}$$

$$\frac{d^2\sigma}{dt\,d\varphi} = \frac{d\sigma_T}{dt\,d\varphi} + \varepsilon\frac{d\sigma_L}{dt\,d\varphi} + \sqrt{2\varepsilon(\varepsilon+1)}\,\frac{d\sigma_{LT}}{dt\,d\varphi}\cos\varphi_\pi + \varepsilon\frac{d\sigma_{TT}}{dt\,d\varphi}\cos 2\varphi_\pi$$

- In t-pole approximation:

$$\sigma_L \propto \frac{-t\,g^2_{\pi NN}(t)}{\left(t-m^2_\pi\right)^2}\,Q^2\,F^2_\pi(Q^2,t)$$

- In most analyses F_π is **extracted** from σ_L data using a model incorporating pion electroproduction (we use VGL/Regge)

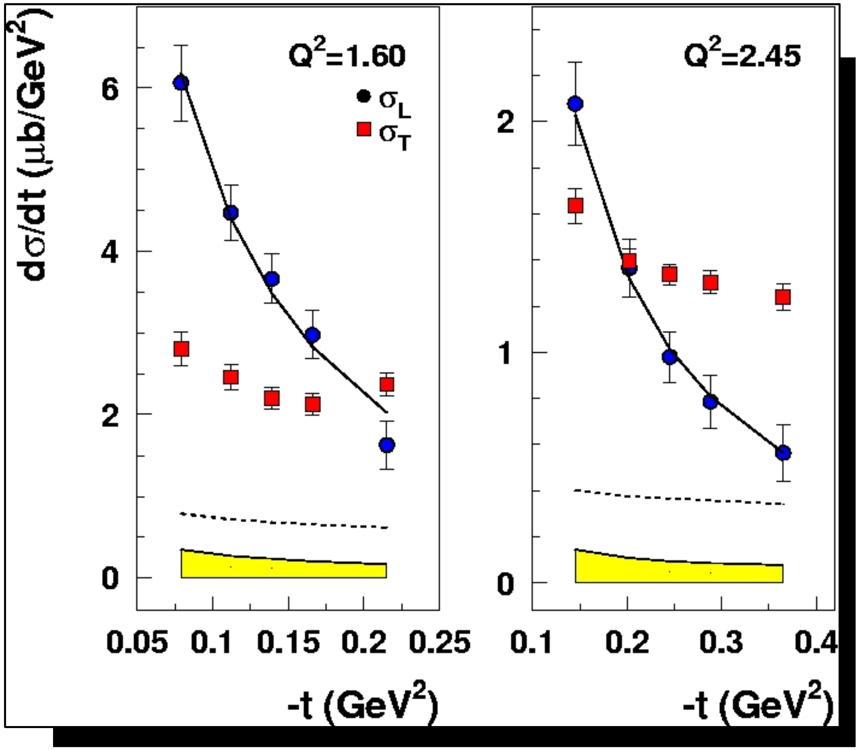
Comparison to VGL Model

- F_π was determined by comparing σ_L to a Regge calculation by Vanderhaeghen, Guidal, Laget (*VGL, PRC **57**(1998)1454*)
  - Model parameters fixed from pion photo-production, free parameters: F_π and F_ρ.

$$F_\pi = \frac{1}{1 + Q^2/\Lambda_\pi^2}$$

Fit to σ_L to model gives F_π at each Q^2

T. Horn et al., Phys. Rev. Lett. 97, 192001 (2006)

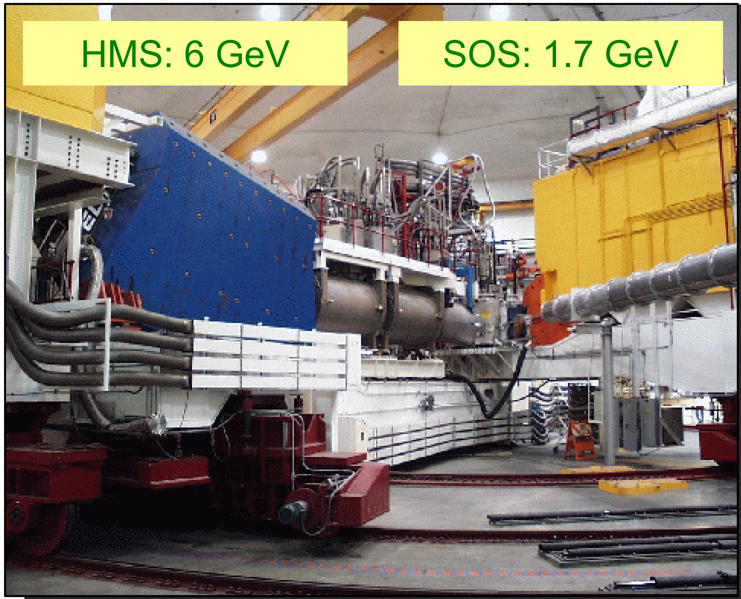


Λ_π^2=0.513, 0.491 GeV^2

- Note: pQCD calculations predict Λ_π^2~0.1 in this kinematic regime

πCT – pion electroproduction at even higher Q^2

- During πCT experiment (see Xin's talk) also took π production data at high and low ε allowing for L-T separation
  - Q^2=2.15, 4.0 GeV^2
  - Targets: LH^2, LD^2, ^{12}C, ^{63}Cu, ^{197}Au – focus here is on H^2, further analysis of nuclear targets underway



Exp	Q^2 (GeV^2)	W (GeV)	|t| (Gev)^2	E_e (GeV)
F_π-1	0.6-1.6	1.95	0.03-0.150	2.445-4.045
F_π-2	1.6,2.45	2.22	0.093,0.189	3.779-5.246
πCT	2.15, 4.0	2.2	0.16-0.44	4.021-5.012

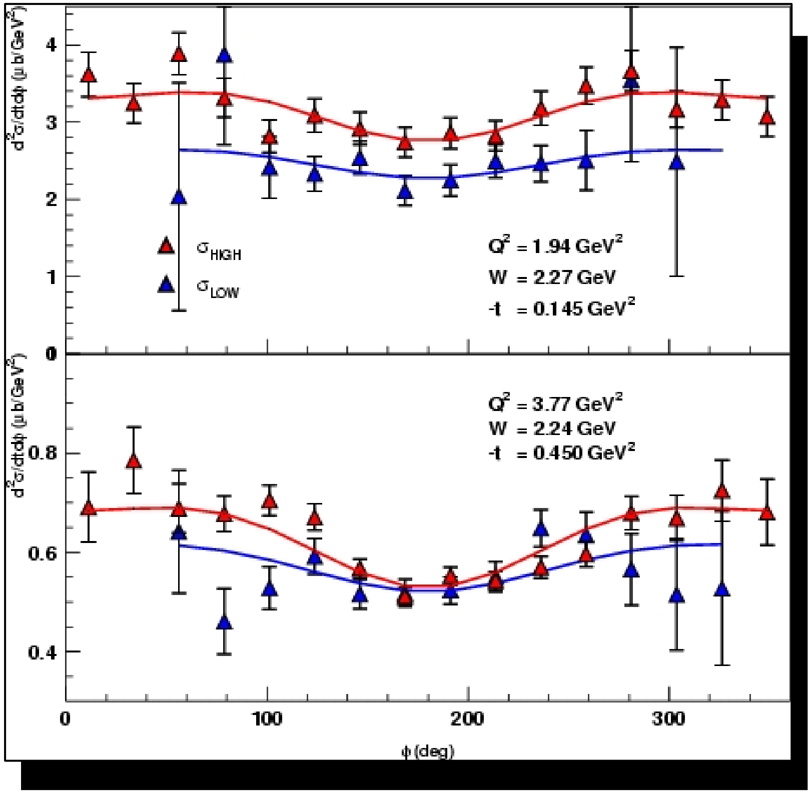
πCT: higher Q^2, larger -t

πCT Cross Section Extraction

- Compare experimental yields to Monte Carlo of the experiment
  - Model for $H(e,e'\pi^+)$ based on pion electroproduction data
  - Radiative effects, pion decay, energy loss, multiple scattering
  - COSY model for spectrometer optics

$$\sigma_{exp} = \frac{Y_{exp}}{Y_{SIMC}}\sigma_{model}$$

- Extract σ_L by simultaneous fit using measured azimuthal angle (φ_π) and knowledge of photon polarization (ε).

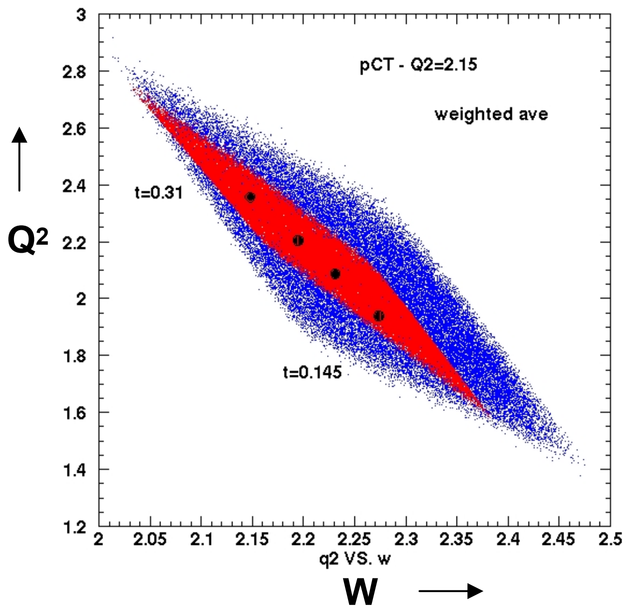


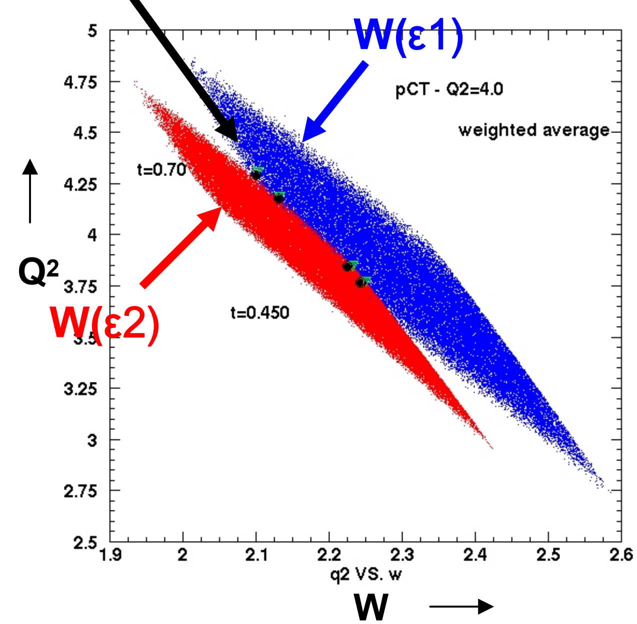
$$\frac{d^2\sigma}{dtd\varphi} = \varepsilon\frac{d\sigma_L}{dtd\varphi} + \frac{d\sigma_T}{dtd\varphi} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dtd\varphi}\cos\varphi_\pi + \varepsilon\frac{d\sigma_{TT}}{dtd\varphi}\cos 2\varphi_\pi$$

πCT – Analysis Issues

- Typically place cut on W/Q² to equalize phase space – cannot do this here
- Solution: central W/Q² from geometric mean of high/low ε points

$$\overline{W} = \tfrac{1}{2}\left(W(\varepsilon_1) + W(\varepsilon_2)\right)$$

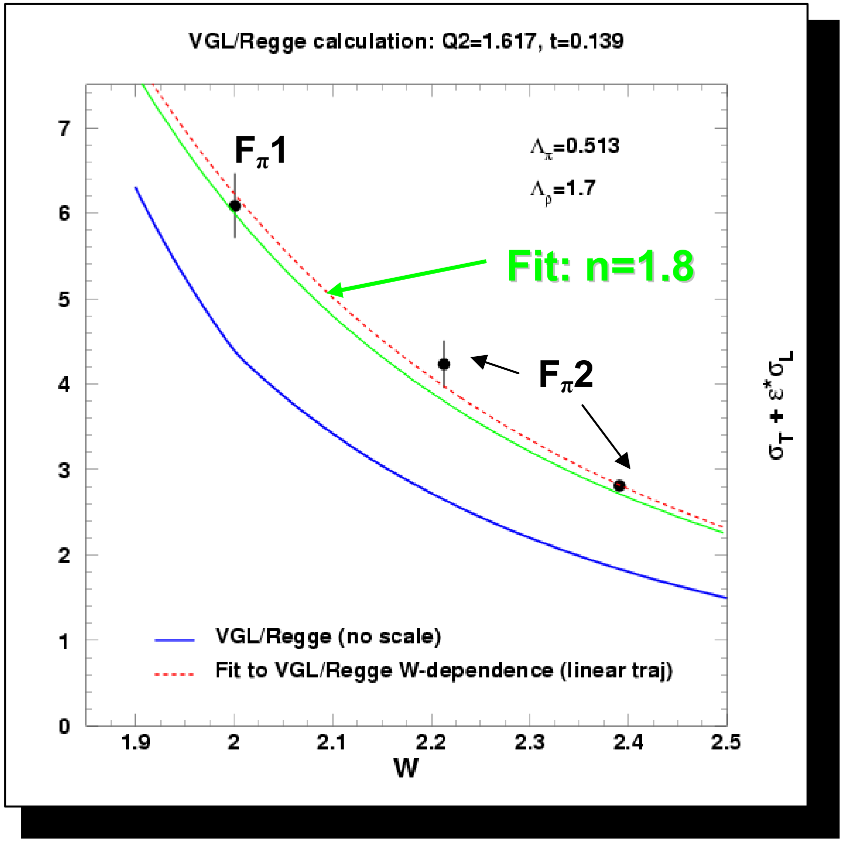




not so good

πCT – cross section W-dependence

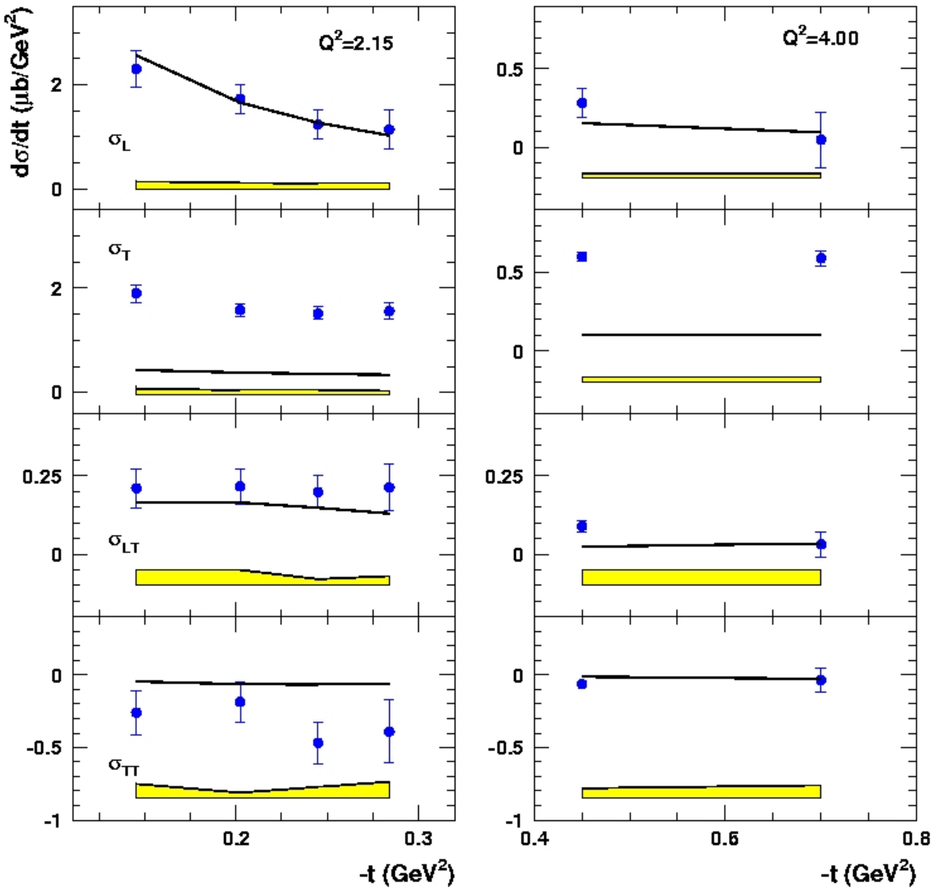
- σ_π depends on W, -t, Q2
- Cross section W-dependence given by: $(W^2-M^2)^n$
  - $F_\pi1/F_\pi2$ data suggest that a n~2 is appropriate
- πCT data were taken at central W=2.2 GeV
  - Relatively small sensitivity to variations in W, ~1% at Q^2=2.15 GeV^2



- W-dependence of σ_π makes sense – but what about –t and Q2?

πCT – separated cross sections t-dependence

- VGL/Regge describes σ_L reasonably well
  - Fit to the t-dependence allows for extracting F_π
- σ_T contributes significantly at Q^2=4.0 GeV^2
- Interference terms →0 as Q^2 increases

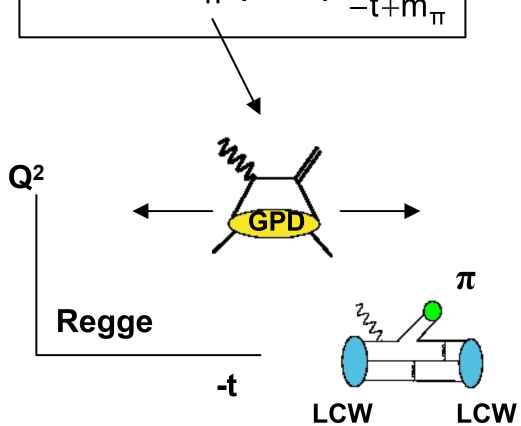


Λ_π^2=0.518 GeV^2

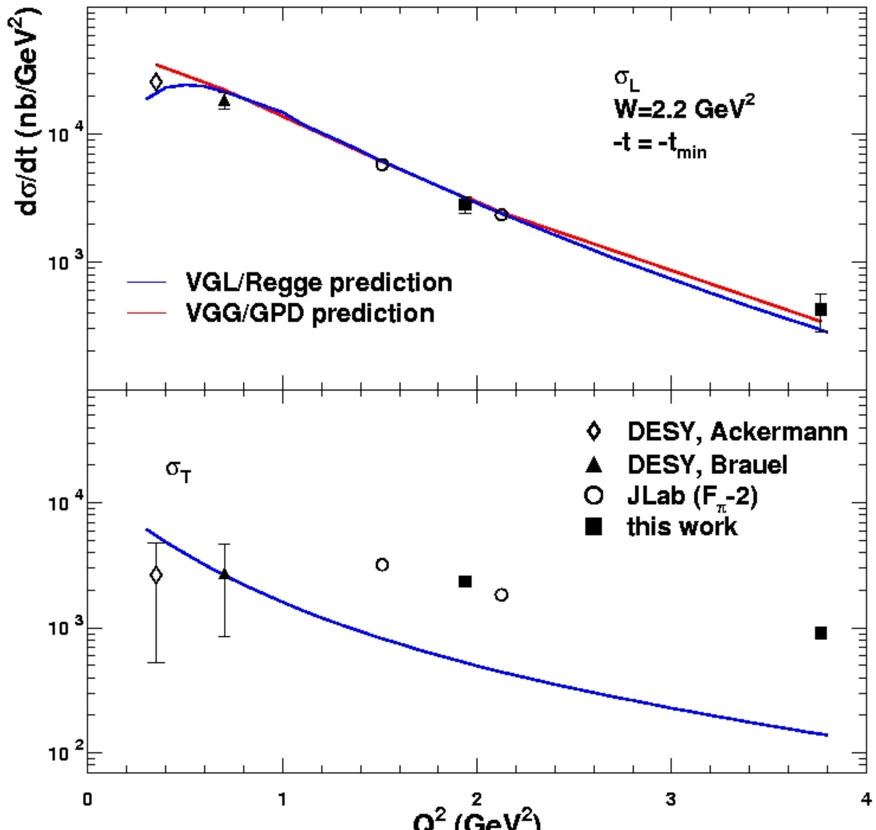
Cross Section Models Constraints

- Both VGG/GPD and VGL/Regge models describe the Q^2 dependence of the data quite well
  - VGG includes a parameterization of F_π
  - Data will provide a constraint on models at high Q^2.

$$\boxed{\widetilde{E} \sim Q\, F_\pi(Q^2)\, \frac{g_{\pi NN}}{-t+m_\pi^2}}$$



Errors are statistical only



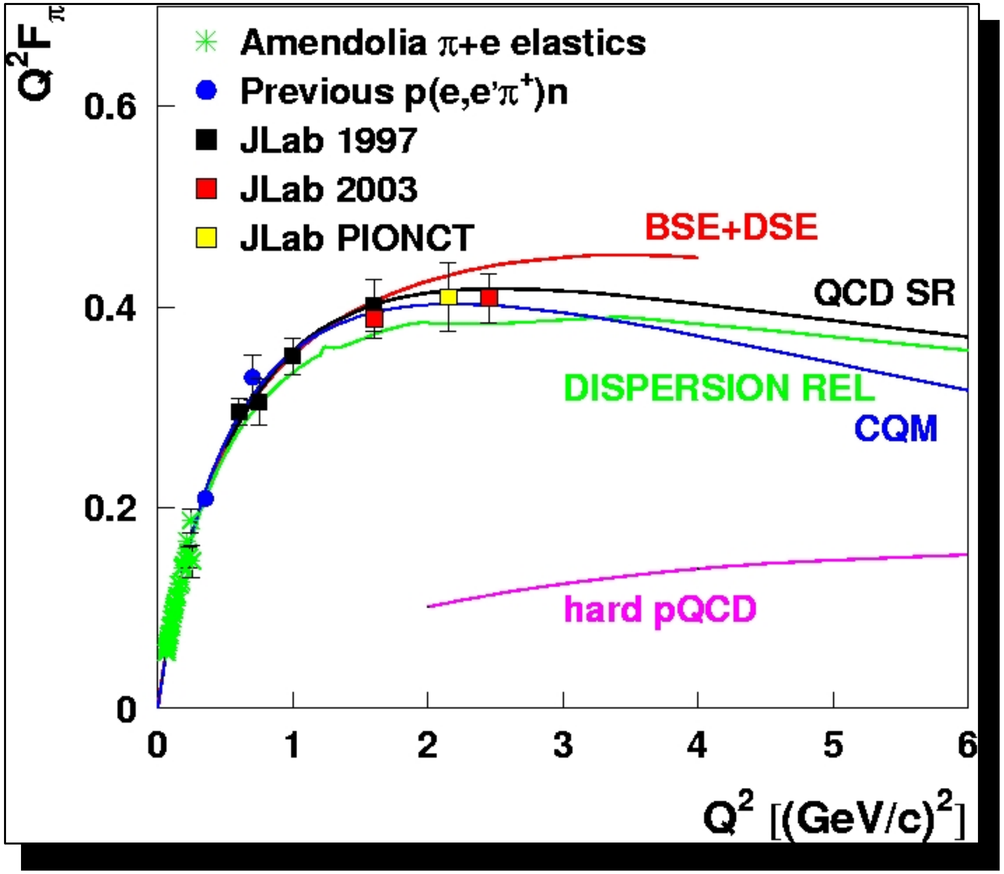
H. Ackermann et al., Nucl. Phys. **B137,** 294 (1978)

P. Brauel et al., Z. Phys. **C3,** 101 (1979)

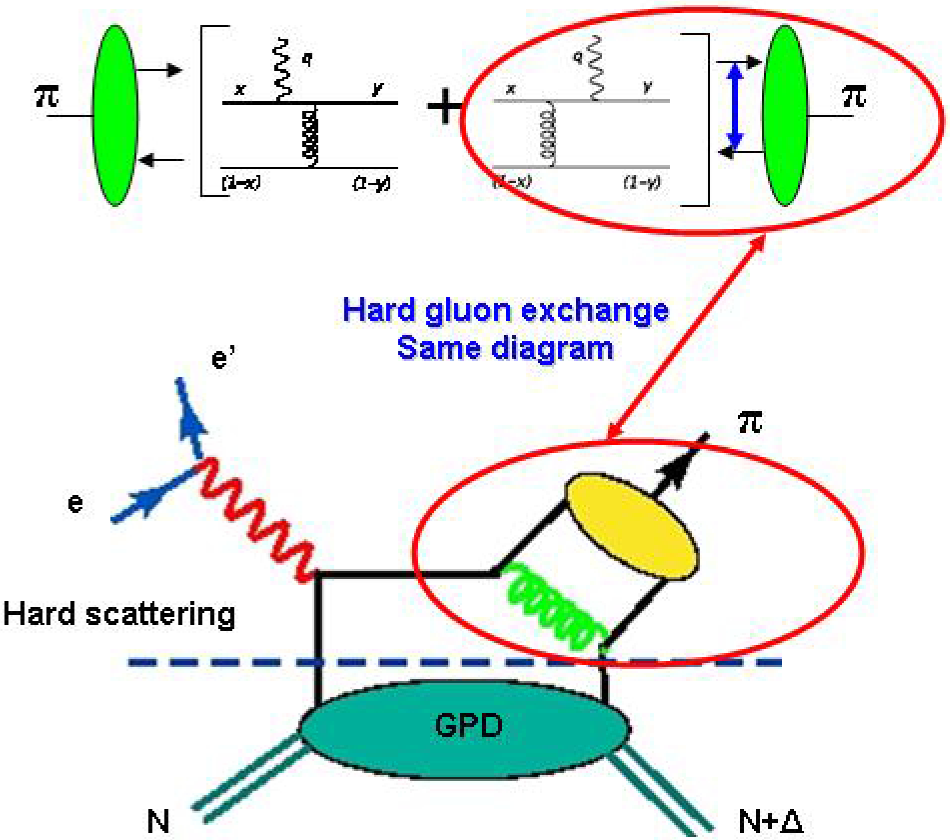
T. Horn et al., Phys. Rev. Lett. 97, 192001 (2006)

F_π Results including πCT

- πCT new point consistent with previous JLab data
  - Gives confidence in the data analysis
- F_π not asymptotic in this kinematic regime
  - Suggests soft contributions dominate over hard term at accessible Q^2 values



Hard Scattering Picture



$H(x,\xi,t)$ $E(x,\xi,t)$

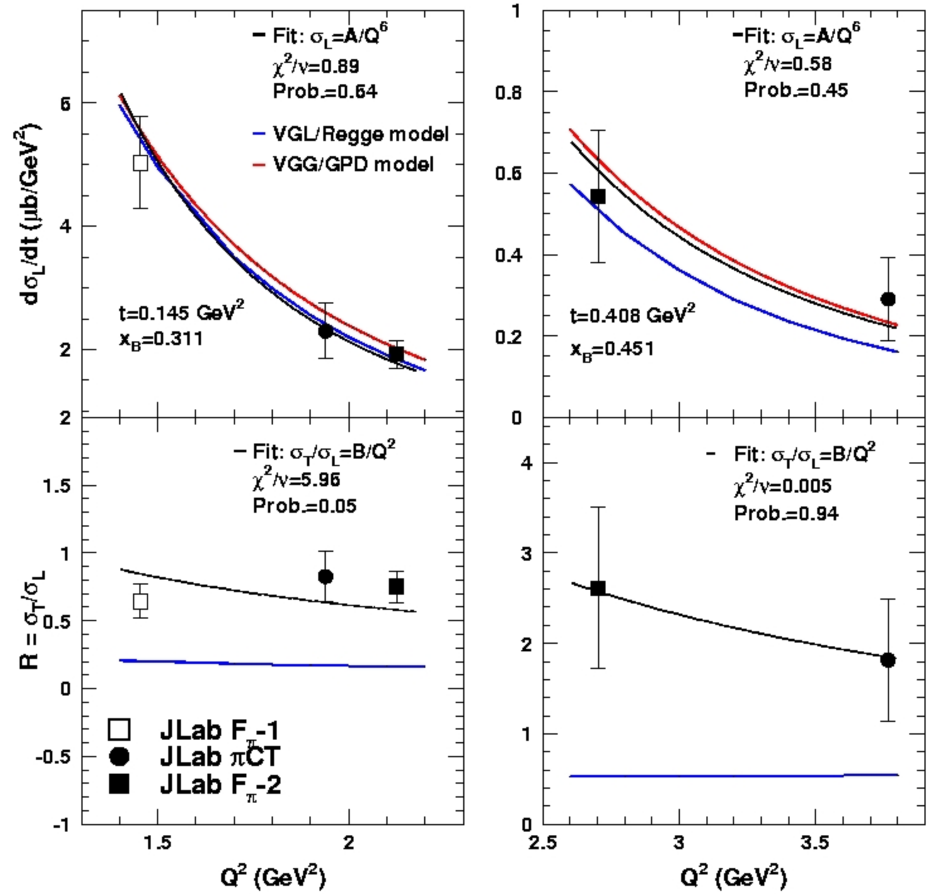
$\tilde{H}(x,\xi,t)$ $\tilde{E}(x,\xi,t)$

- Factorization: separate soft/hard processes
  - Essential for accessing GPD's in exclusive reactions
- Factorization requirements:
  - $\sigma_L \sim Q^{-6}$ and $\sigma_T \sim Q^{-8}$
  - Similar predictions for LT and TT
- Onset of color transparency
- F_π is asymptotic

Scaling Behavior

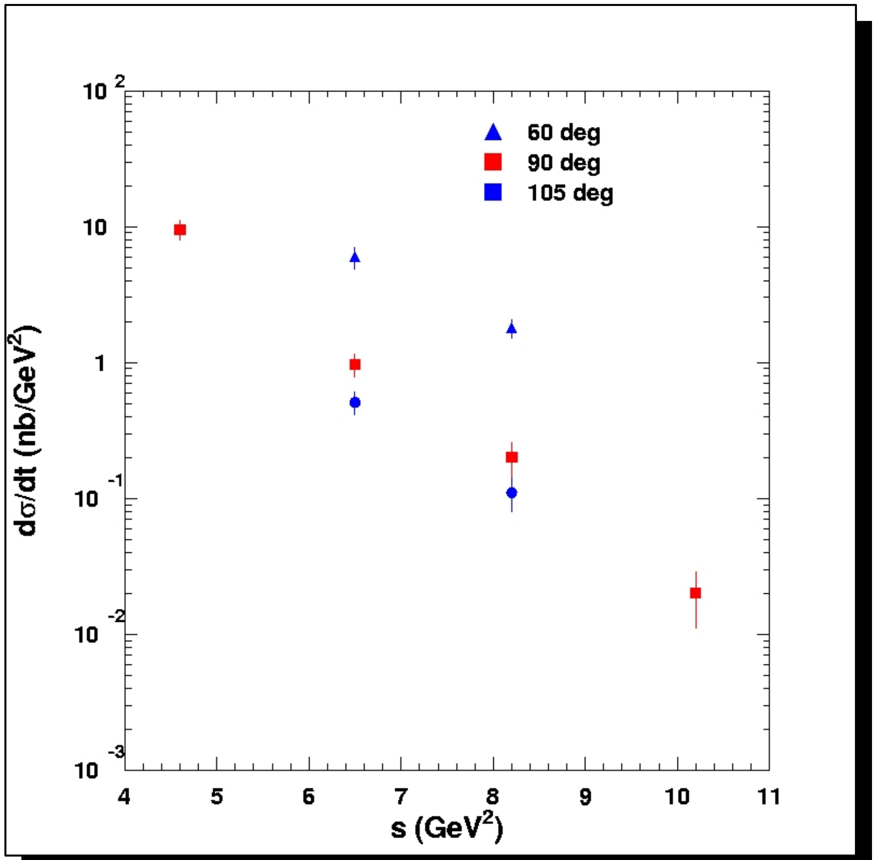
- Asymptotic scaling predicts $\sigma_L \sim 1/Q^6$ and $\sigma_T/\sigma_L \sim 1/Q^2$
- Similar ratios for σ_{LT}, σ_{TT}, each transverse term contributes 1/Q

x	σ_L fit	σ_T/σ_L fit
0.311	5.11±1.04	-0.89±1.35
0.451	3.77±2.90	2.18±3.19

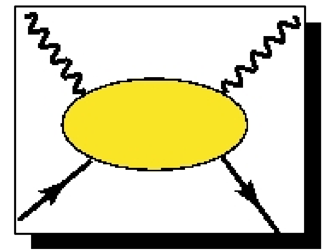


- Result suggestive, but not sufficient for factorization test - need higher energy – 12 GeV proposal

Compton Scattering Scaling Predictions



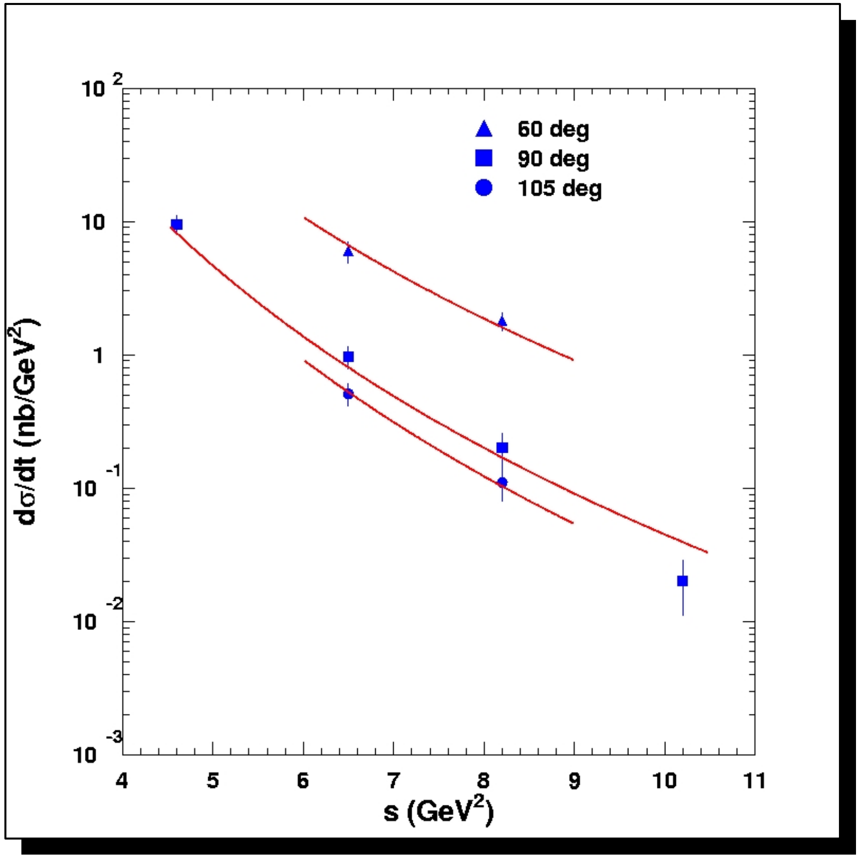
M. A. Shupe et al., Phys. Rev. D19, 1921 (1979)



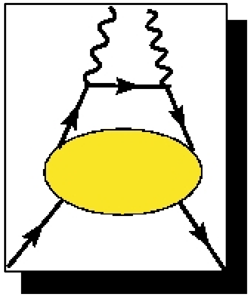
- Expected scaling behavior
  - Fixed θ^*: $d\sigma/dt \sim s^{-n(\theta)}$, $n^{hard(\theta)} = 6$
- Experimental fits are consistent with the prediction within the uncertainty
  - But is this sufficient?

θ	n^{data}
60	5.9±0.3
90	7.1±0.4
105	6.2±1.4

Compton Scattering and Soft Contributions



M. A. Shupe et al., Phys. Rev. D19, 1921 (1979)



- Soft contributions can result in deviations from expected scaling behavior *(A. Radyushkin, Phys. Rev. D58 (1998) 114008.)*
  - Fixed θ^*: $d\sigma/dt \sim s^{-n(\theta)}$, $n^{hard(\theta)} = 6$

θ	n^{data}	n^{soft}
60	5.9±0.3	6.1
90	7.1±0.4	6.7
105	6.2±1.4	7.0

$d\sigma/dt \sim A\, s^{-n}$

Summary

- πCT extends JLab separated pion electroproduction cross section data set to Q^2=4.0 GeV^2
  - Good agreement between extracted F_π values gives confidence in data analysis
  - Constraint on models at Q^2=4.0 GeV^2 and higher -t
- F_π not asymptotic in this kinematic regime
  - Suggests soft contributions dominate over hard term at accessible Q^2 values
- Asymptotic scaling tests not sufficient for conclusions on factorization
  - not necessarily un-expected – see Compton scattering results
  - need higher energies and longer lever arm – 12 GeV proposal